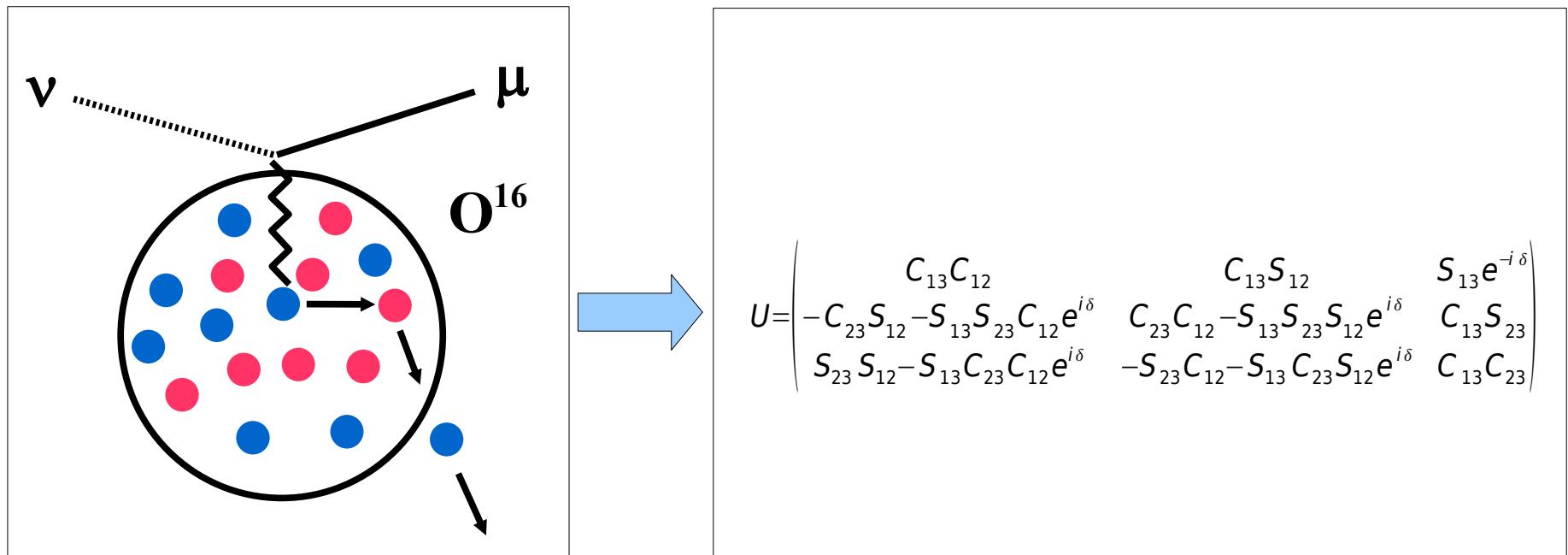


Why understanding neutrino interactions is important for oscillation physics



Introduction * Cross-Sections * Effects on Experiments



Chris Walter / Duke University
 $\text{\textit{NuInt07 FNAL}} / \text{May 30th 2007}$

What's the current picture of neutrino oscillations?

$$P_{F_1 F_2} = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

3 —————

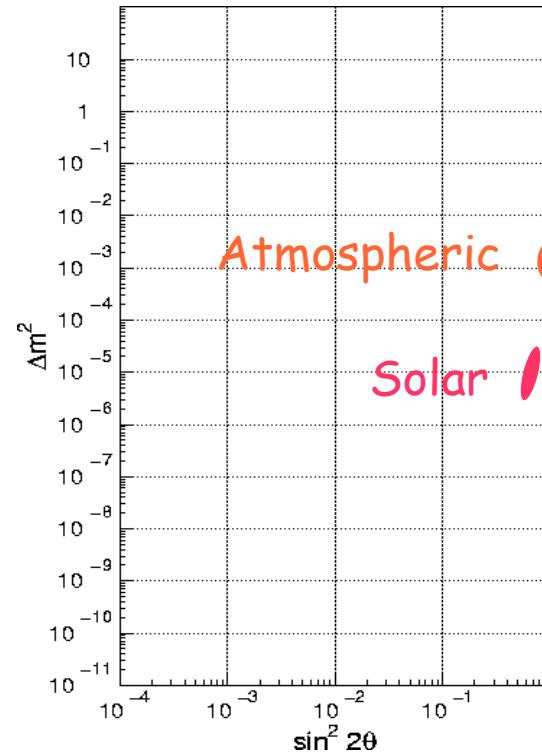
$$\Delta m^2_{\text{atm}} \sim 10^{-3} \text{ eV}^2$$

2 —————

1 $\Delta m^2_{\text{sun}} \sim 10^{-5} \text{ eV}^2$

$$\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$$

Three neutrinos allow
two mass differences!



$$C_{xy} = \cos(\theta_{xy}) \quad S_{xy} = \sin(\theta_{xy})$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmos Osc

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix}$$

???????

$$\begin{pmatrix} C_{13} & 0 & S_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -S_{13} e^{i\delta} & 0 & C_{13} \end{pmatrix}$$

Solar Osc

$$\begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

muons "disappear" Can make electrons "appear" electrons "disappear"

What can we learn with oscillation experiments?

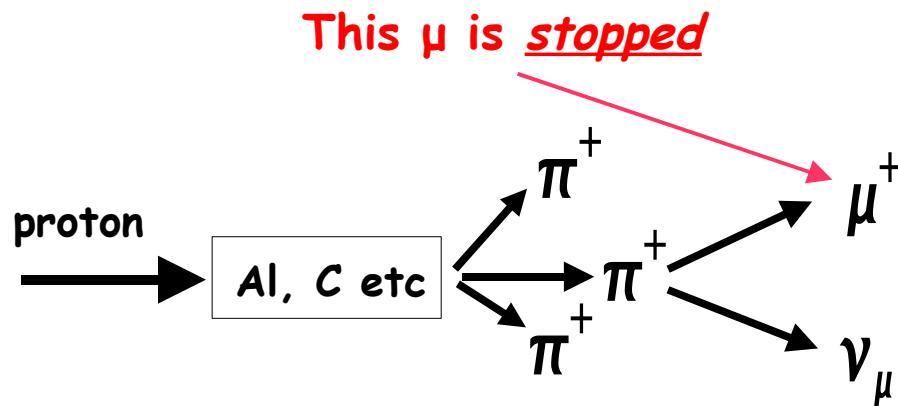
- What is the mass hierarchy?
- What are precise values of Δm^2 , $\sin^2 \theta_{23}$
- Is θ_{13} non zero?
- Is CP violated?

Important issues in ν oscillation experiments.

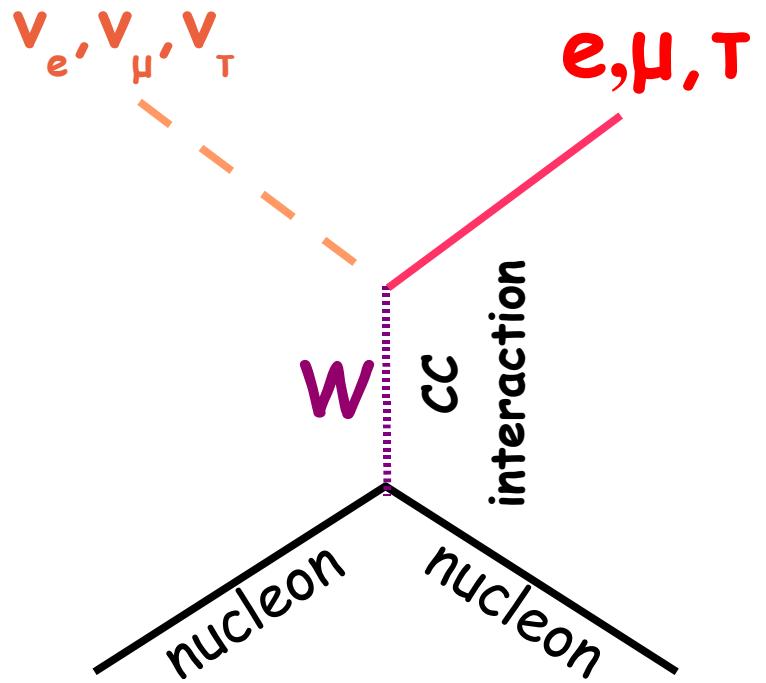
- We always measure ν flux * cross-section
- We measure with a detector which has different efficiencies for different cross-section channels .
- We need to be able to predict (or measure) both the non-oscillated spectra and interpret distortions.
- Starting with MINOS, the statistics from long-base line oscillation experiments are becoming comparable with the systematic errors caused by nuclear effects.

“Seeing” Neutrinos

Production



Interaction



Threshold for producing each lepton:

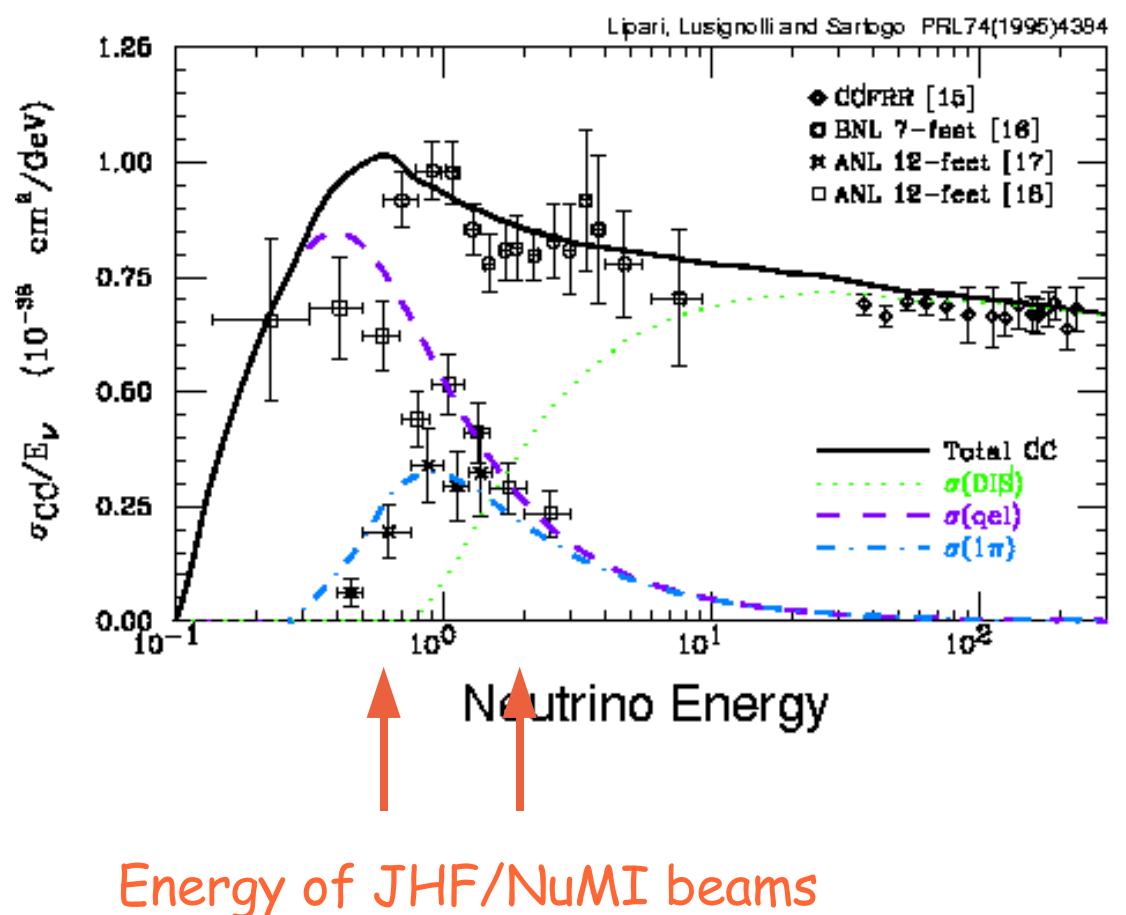
$$E_{\nu e} > 0.15 \text{ MeV}$$

$$E_{\nu \mu} > 110 \text{ MeV}$$

$$E_{\nu \tau} > 3500 \text{ MeV}$$

Different neutrino experiments see different proportions of cross-sections

- For $\sim 300\text{km}$ baselines,
 $\Delta m^2 \sim 3 \times 10^{-3}$,
The flux is maximally oscillated $<\sim 1 \text{ GeV}$
- Scales with baseline:
 $750 \text{ km} < \sim 2.5 \text{ GeV}$

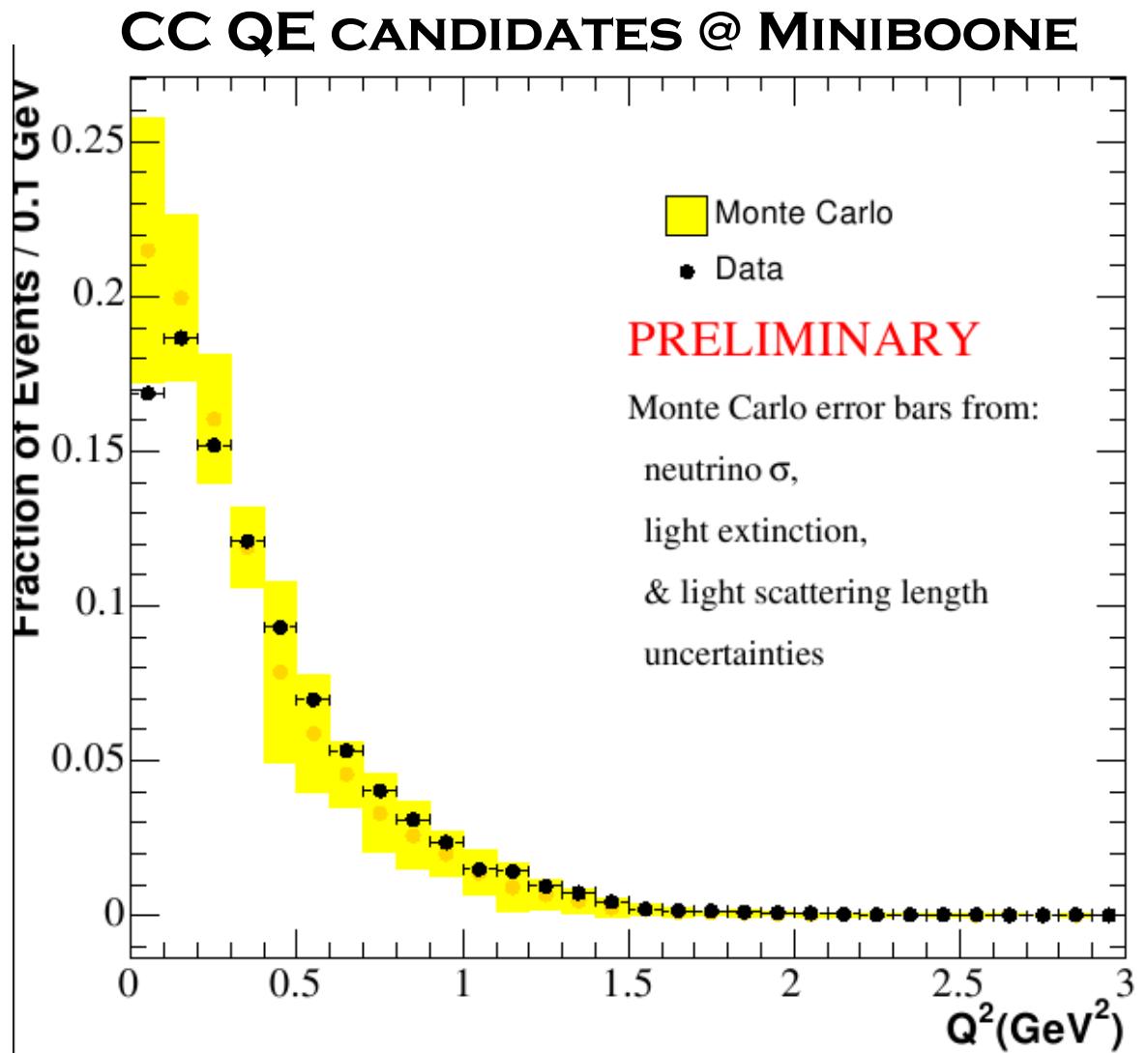


There are still things we don't understand!

Example: Low Q² effect

Even after correcting for what we know about at low momentum transfers the data is suppressed relative to the MC.

Seen in K2K(kton,scifi, scibar) and Miniboone.

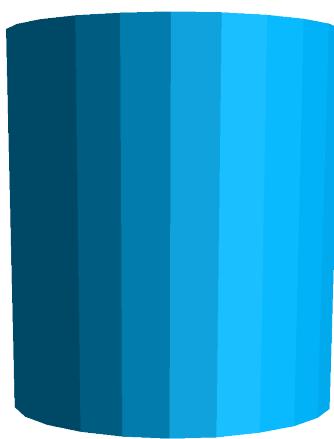


Using Near and Far Detectors.

Number:

$$N_1 \text{ Events}$$

Flux

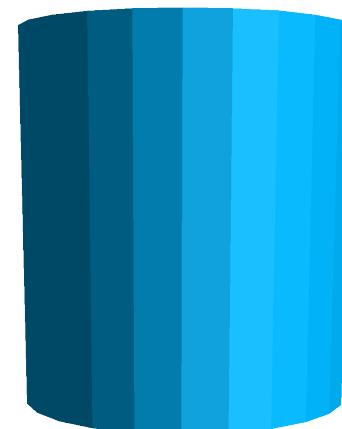


Detector 1

We use a detector near to the beam to measure the number and energy spectra of the produced neutrinos.

$$N_2 = \alpha \cdot N_1 \cdot \text{Ratio}(2/1)$$

Function of Flux, X-sec, efficiencies.
cancels for identical detectors and fluxes



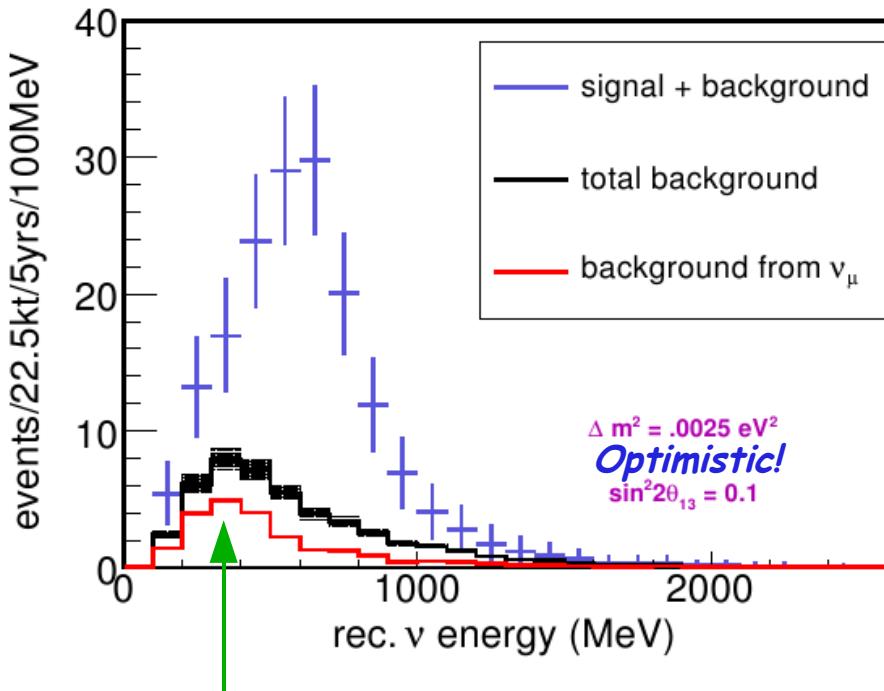
Detector 2

Then we predict how many we should see based on what we measured and the divergence of the beam.

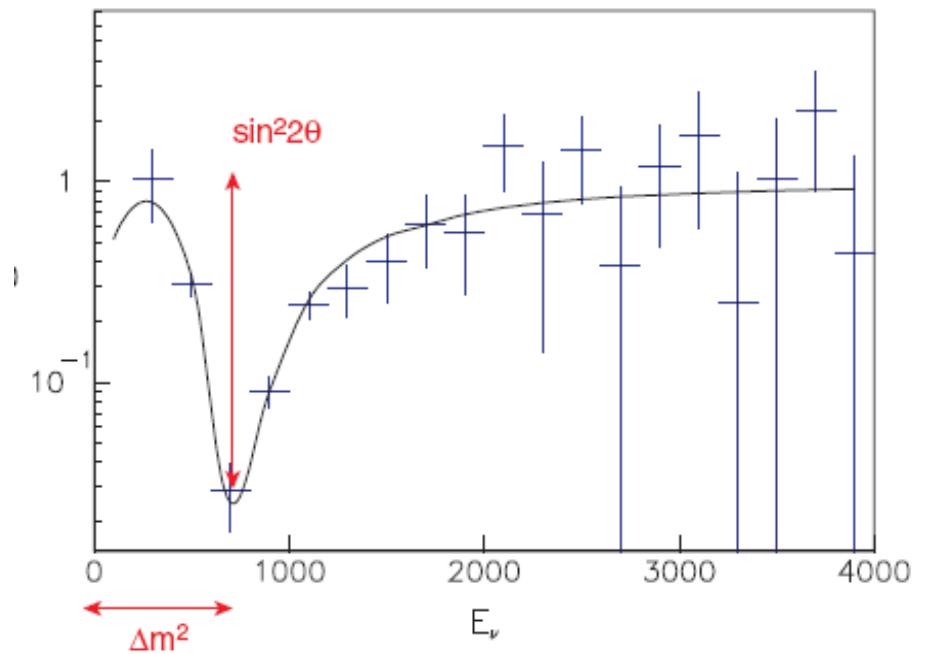
Often not good enough! There are differences in flux and efficiencies.

Two types of physics analysis: disappearance and appearance

ν_e appearance:
determine θ_{13}



ν_μ disappearance:
determine θ_{23} and Δm^2_{23}



For appearance three main types of background:
intrinsic ν_e , misidentified π^0 , mis-identified charged μ .

Must control to the few per mill level

Important x-secs to know

Quasi-Elastic

V-A

Llewellyn-Smith 1972

Must set MA(QE) Value

Single Pion

Resonance production

Rein & Seghal 1981

Many Other Models + MA(1π)

Coherent Pion

Rein & Seghal/?

Suppress CC production?

Deep Inelastic Scattering

GRV 94 parton
distribution

Bodek/Yang 2001

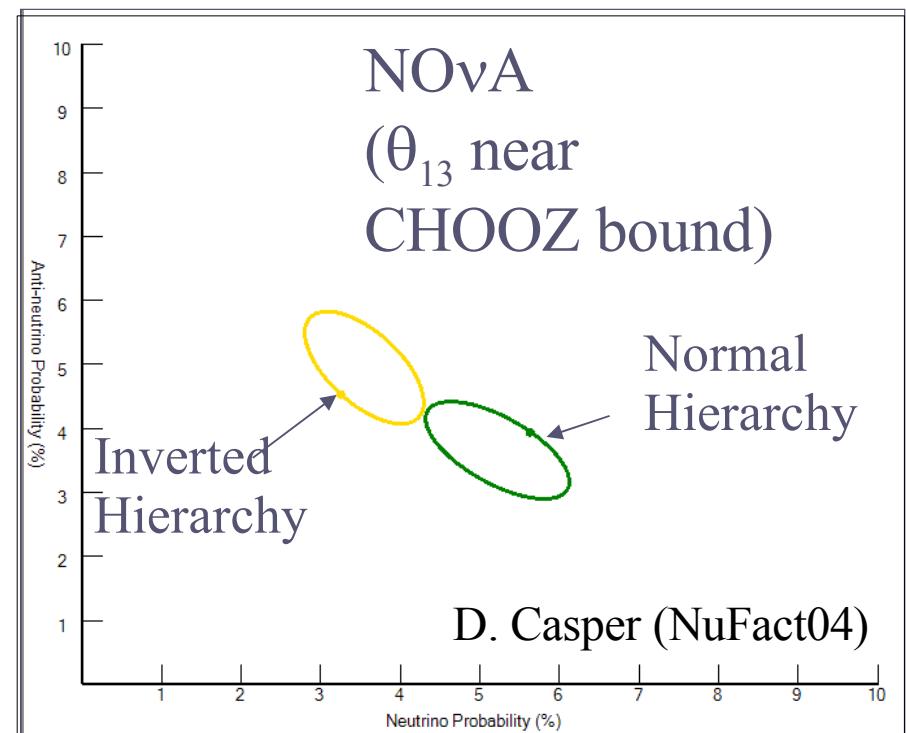
Nuclear Effects

Fermi motion

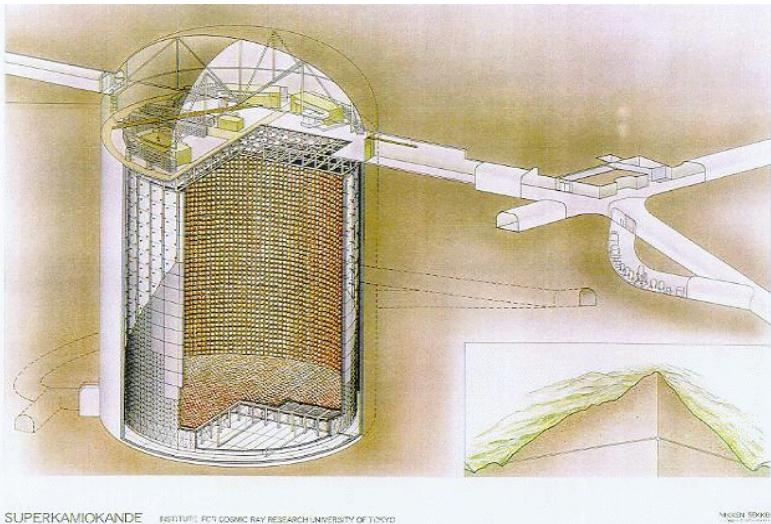
Pauli blocking

Nuclear

Note: also will need comparable x-secs for anti-neutrinos for future experiments.



WC E_ν Reconstruction (assuming QE)

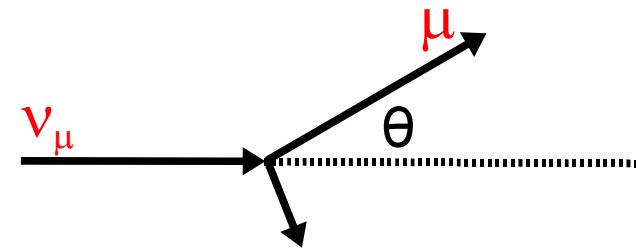


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH, UNIVERSITY OF TOKYO

In Water Cherenkov detectors not every particle is above Cherenkov threshold.

Luckily, in a Quasi-Elastic reaction, even if only the muon is visible we can reconstruct the neutrino energy!

If the interaction is **non** Quasi-Elastic then the reconstructed energy will be incorrect.



$$E_\nu = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + p_\mu \cos(\Theta_\mu)}$$

m_N = Neutron mass

E_μ = Muon energy

m_μ = Muon mass

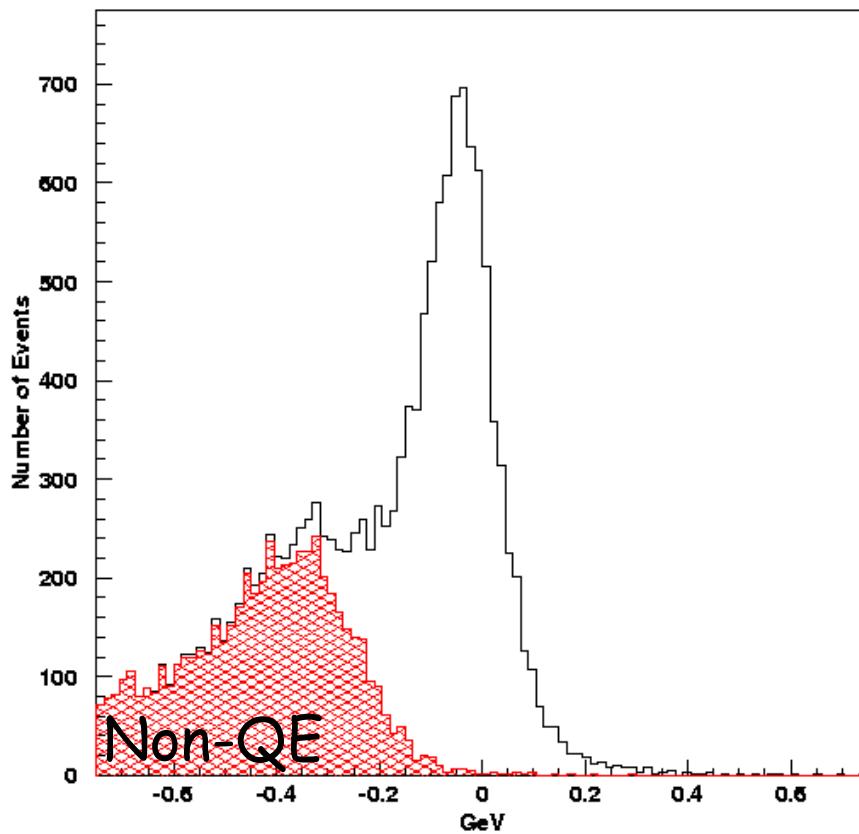
p_μ = Muon momentum

Θ_μ = Muon angle wrt beam

Non-QE interactions and E_{ν}

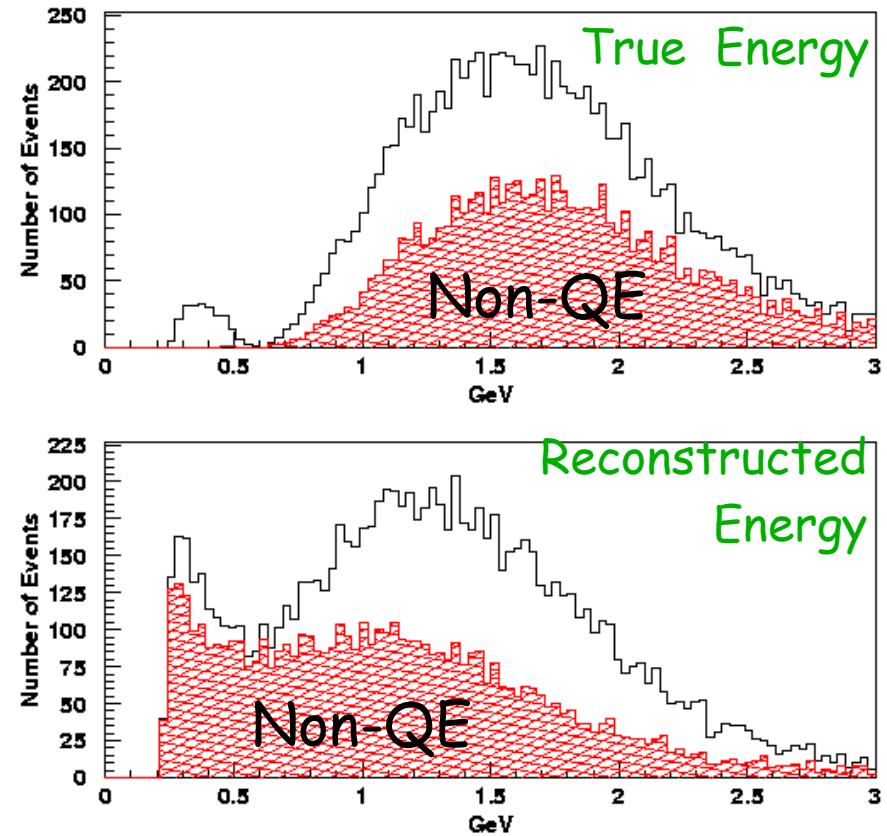
Reconstruction

Example: K2K Flux MC



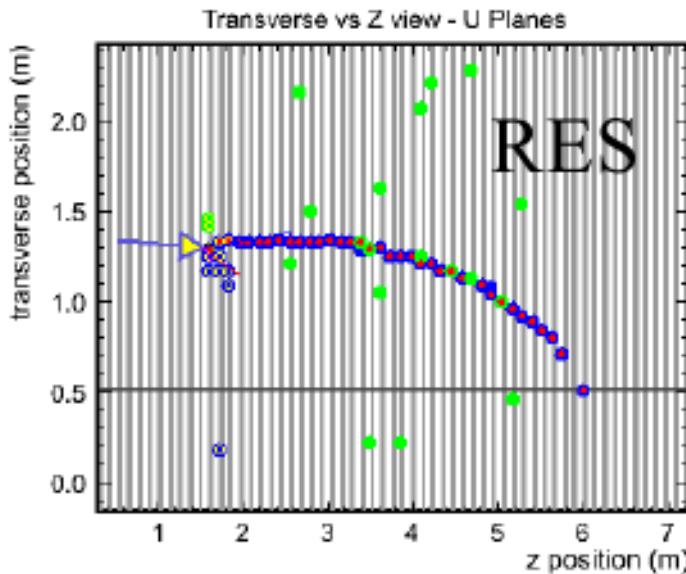
Non-QE

True - Reconstructed Energy



Non-QE reconstructs at
low-energy in the oscillation dip!

Calorimetric Detectors (Example: MINOS)

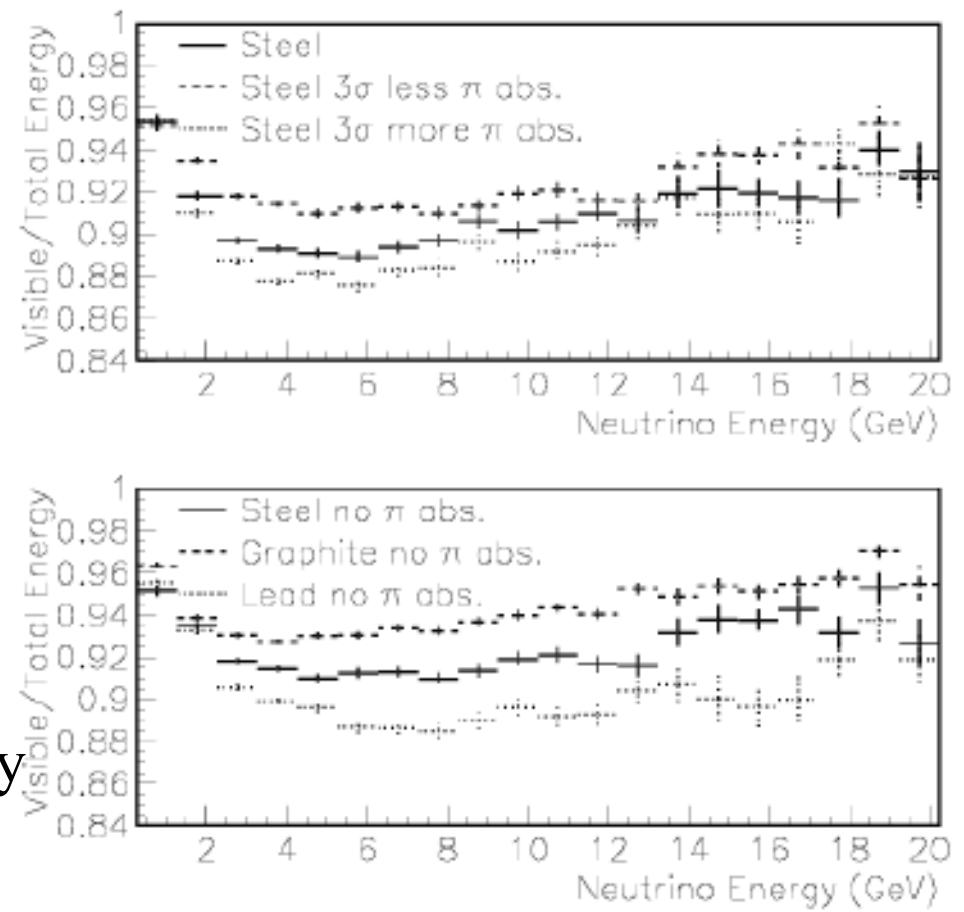


In a calorimetric detector all of the particles are visible and you add up all of the visible energy to get the neutrino energy.

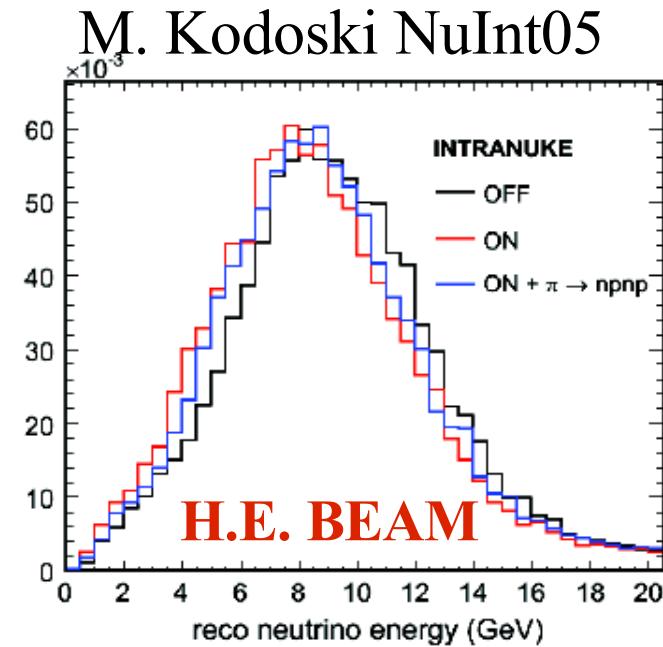
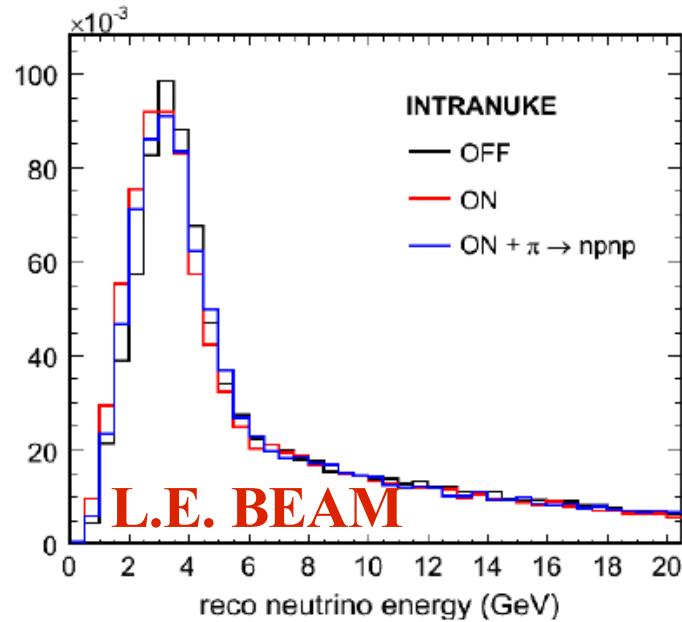
$$E_{\nu} = E_{\mu} + E_{\text{shower}}$$

Nucleus absorbs and re-scatters pions.
If they “disappear” so does the energy.

D. Harris NuFact06



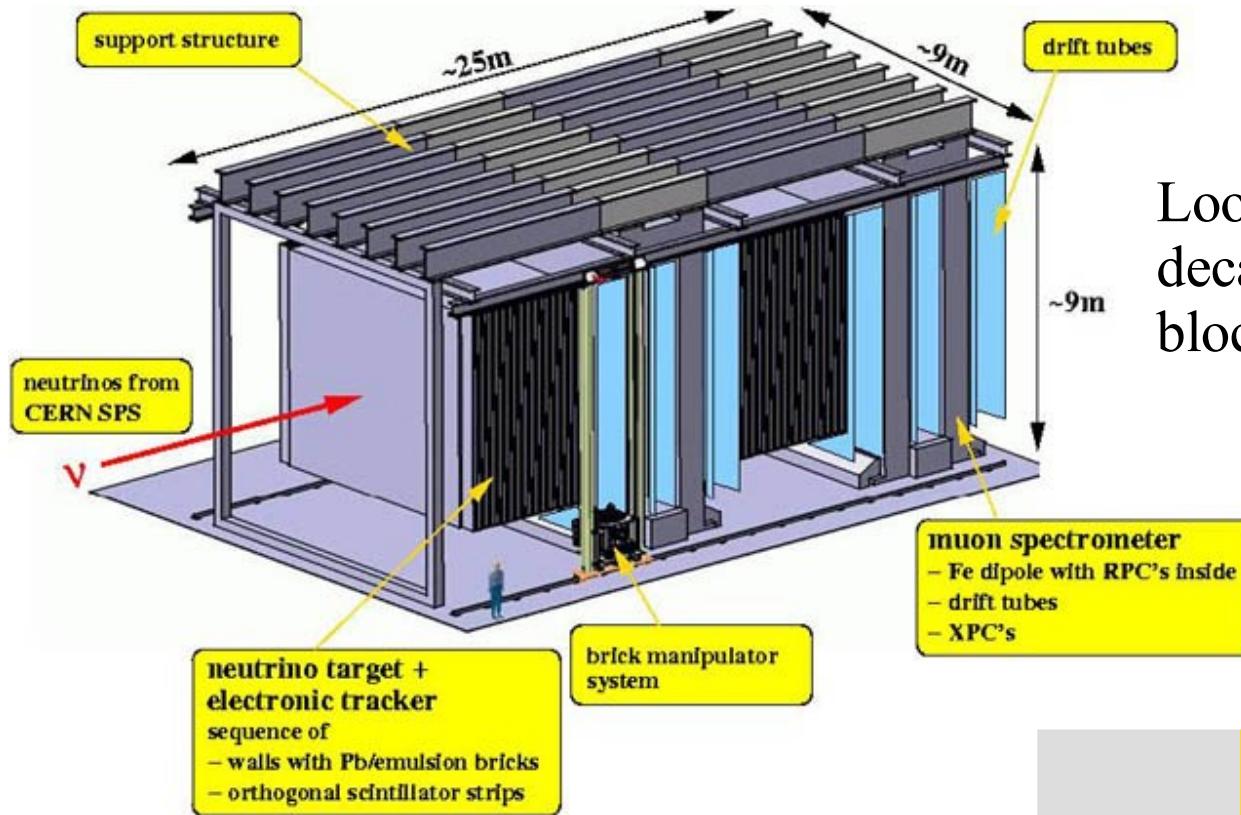
Effect of absorption:



MINOS uses a hadronic energy scale uncertainty of $\sim 10\%$:
The 2nd largest systematic error on the Δm^2 .

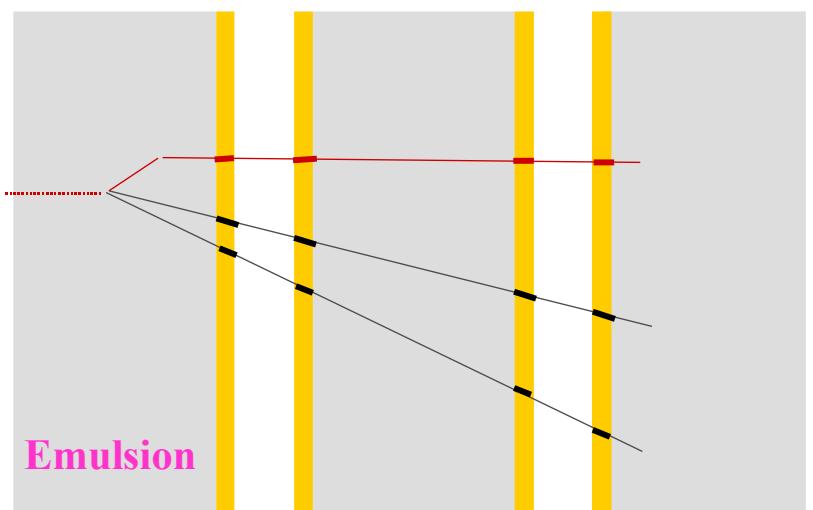
Also very important: Hadronic shower shapes for NC vs. CC separation

Another kind of x-sec bkg: Opera



Look for a kink from the decay of the tau in a emulsion block.

Short Decay:



- Main backgrounds:
- charm decays
 - large angle μ scattering
 - hadron re-interactions

Quasi-Elastic Cross Section

$$\frac{d\sigma_{QE}}{dQ^2} = \frac{M^2 G^2 \cos^2(\theta_c)}{8\pi E_\nu^2} [A(Q^2) - B(Q^2)(s-u) + C(Q^2)(s-u)^2]$$

- $A = 4(m^2/4M^2 + \tau)[(1+\tau)|F_A|^2 - (1-\tau)|F_V^1|^2 + \tau(1-\tau)|\xi F_V^2|^2 + 4\tau\xi \operatorname{Re} F_V^* F_V^2] - m^2/4M^2(|F_V^1 + \xi F_V^2|^2 + |F_A + 2F_p|^2 - 4(1+\tau)|F_p|^2)]$
- $B = -4\tau \operatorname{Re} F_A^*(F_V^1 + \xi F_V^2)$
- $C = 4(|F_A|^2 + |F_V^1|^2 + \tau|\xi F_V^2|^2)$

Where $(s-u) = 4ME_\nu - Q^2/M_\mu$, $\tau = Q^2/4M^2$, $\xi = u_p - u_n$,

F_p is the pseudo scalar form factor, and F_A is the axial vector form factor.

- The vector form factors:
 - $F_V^1 = (G_{Ep} - G_{En} - \tau(G_{Mp} - G_{Mn}))/ (1+\tau)$
 - $\xi F_V^2 = (G_{Mp} - G_{Mn} - G_{Ep} + G_{En})/ (1+\tau)$

Neutrino Interactions

From EM Scattering:

$$\begin{aligned} G_{EP}(Q^2=0) &= 1 & G_{EN}(Q^2=0) &= 0 \\ G_{MP}(Q^2=0) &= 2.79 & G_{MN}(Q^2=0) &= -1.91 \end{aligned}$$

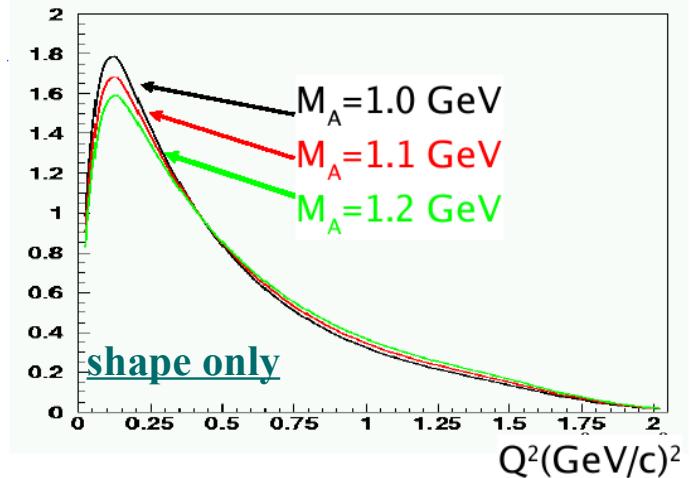
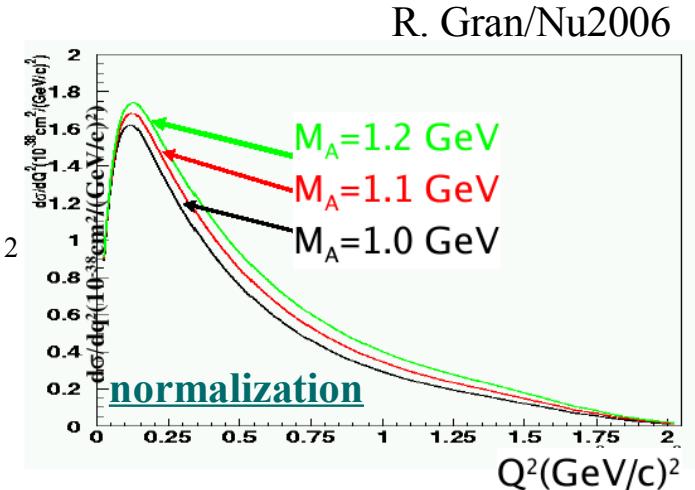
$$G_E^P(Q^2) = \frac{G_M^P(Q^2)}{2.79} = \frac{G_M^n(Q^2)}{-1.91} = G^{dipole}(Q^2) = \left(1 + \frac{Q^2}{0.71(GeV/c)^2}\right)^{-2}$$

Charged Current

$$\begin{aligned} J_\alpha^{1+i2} &= V_\alpha^{1+i2} - A_\alpha^{1+i2} \\ \langle p(p') | J_\alpha^{CC} | n(p) \rangle &= \langle p(p') | V_\alpha^{1+i2} - A_\alpha^{1+i2} | n(p) \rangle \\ \langle p(p') | V_\alpha^{1+i2} | n(p) \rangle &= \bar{u}(p') \left[\gamma_\alpha F_1^V(Q^2) + \frac{i}{2M} \sigma_{\alpha\beta} q^\beta F_2^V(Q^2) \right] u(p) \\ \langle p(p') | A_\alpha^{1+i2} | n(p) \rangle &= \bar{u}(p') \left[\gamma_\alpha \gamma_5 F_A(Q^2) + q_\alpha F_p(Q^2) \right] u(p) \end{aligned}$$

$$F_A(Q^2) = \frac{F_A(0)}{(1+Q^2/M_A^2)^2} \quad , \text{with} \quad F_A(0) = -1.2617 \pm 0.0035$$

$$F_p(Q^2) = \frac{2MF_A(Q^2)}{m_\pi^2 + Q^2}$$



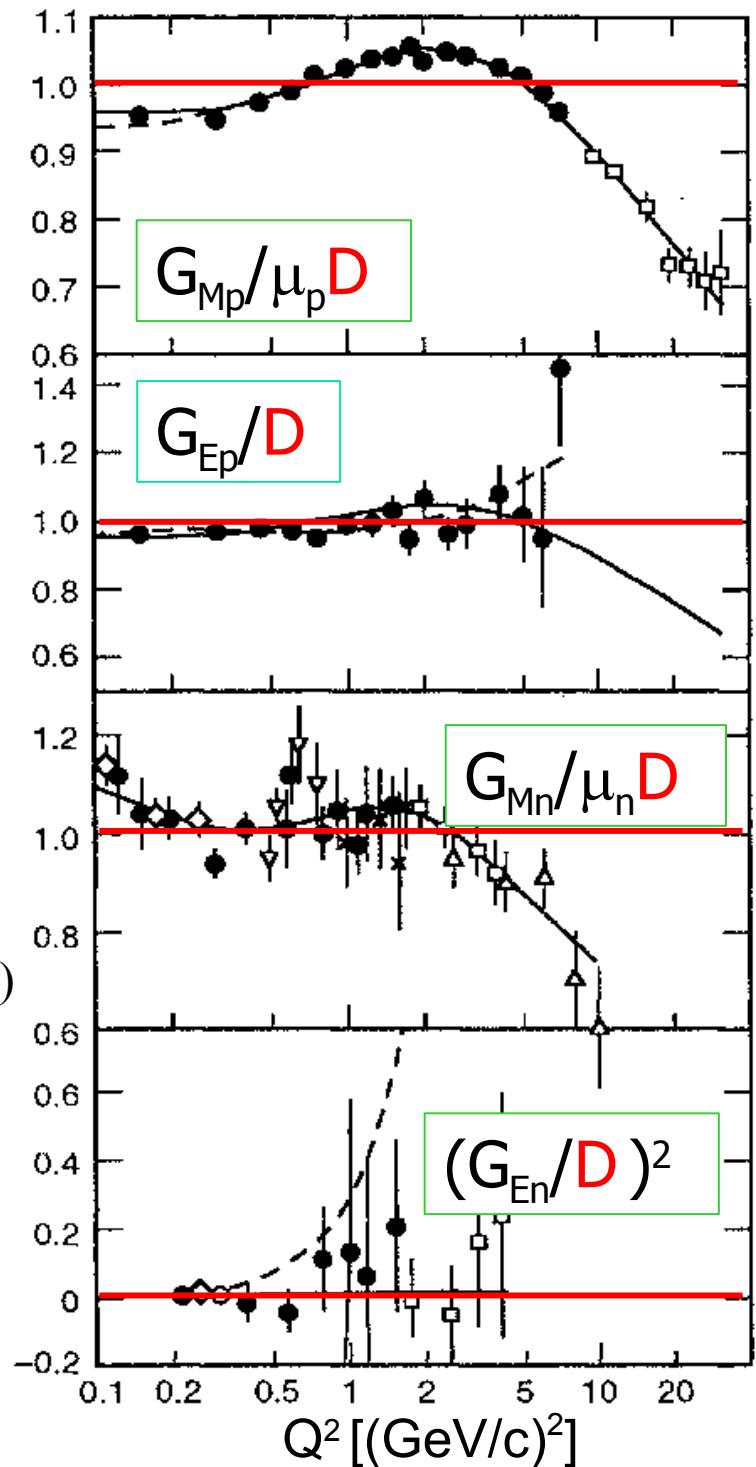
Changing the axial mass changes the shape and the normalization

Nucleon Vector Form Factors

- The simple dipole fit is only good to ~10-20%. New SLAC/JLAB e-p/e-D data shows that vector form factors must be updated.
- New parameters from P.E. Bosted, "Empirical fit to nucleon electromagnetic form factors, Phys Rev C, V 51, 409, '95
(Also E.J.Brash et al, PRC65,051001,2002)

Form Factor	Old	New
G_{En}	0	$-1.25 \mu_n D \tau / (1 + 18.3 \tau)$
G_{Ep}	D	$1 / (1 + .14Q + 3.01Q^2 + .02Q^3 + 1.20Q^4 + .32Q^5)$
G_{Mn}	$\mu_n D$	$\mu_n / (1 - 1.74Q + 9.29Q^2 - 7.63Q^3 + 4.63Q^4)$
G_{Mp}	$\mu_p D$	$\mu_p / (1 + .14Q + 3.01Q^2 + .02Q^3 + 1.20Q^4 + .32Q^5)$
F_p	0	$2M^2 F_A(Q^2) / (m_\pi^2 + Q^2)$

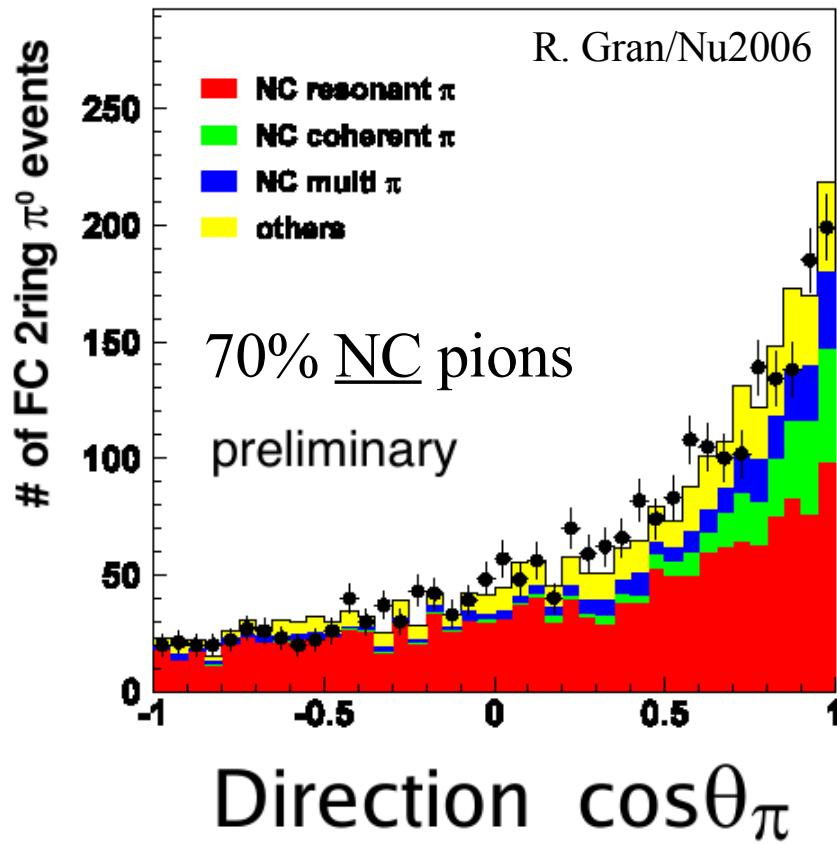
- New cross section is smaller at low Q^2 , and larger at higher Q^2
- $\sim \pm 5\%$ overall difference in $d\sigma_{QE}/dQ^2$
- Changes M_A fit value by .05



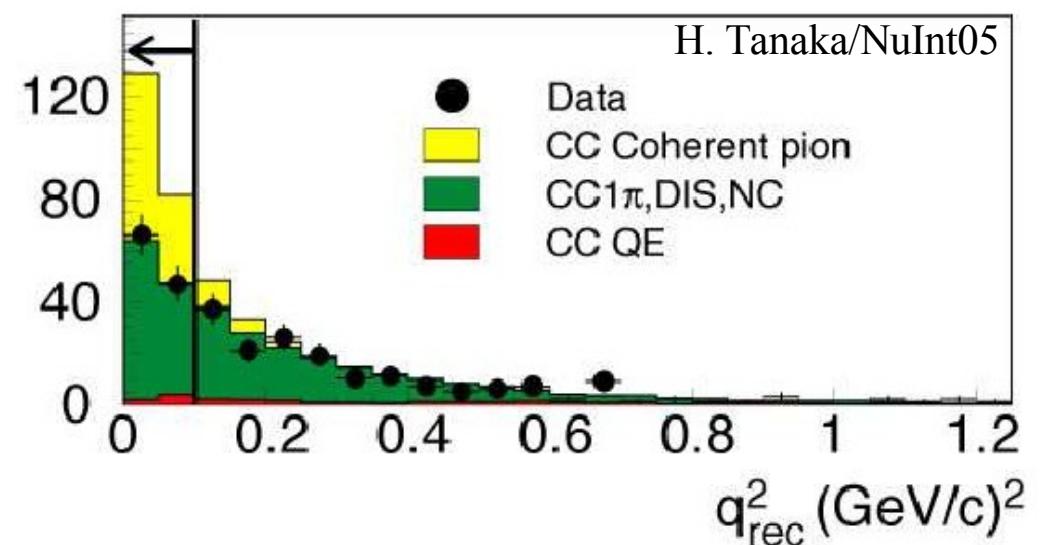
Resonant and coherent pion production

Neutral current production of π largest background for ν_e appearance!

K2K KTON



K2K SCIBAR



Charge current coherent seems to be suppressed/non-existent. .

New theoretical work has addressed this.

DIS (Bodek-Yang at Nulnt01/02)

$$F_2(x) = \sum_i e_i^2 \left(x q_i(x) + x \overline{q_i(x)} \right)$$

$$F_2(x) = \frac{Q^2}{Q^2 + 0.188} F_2(x_w)$$

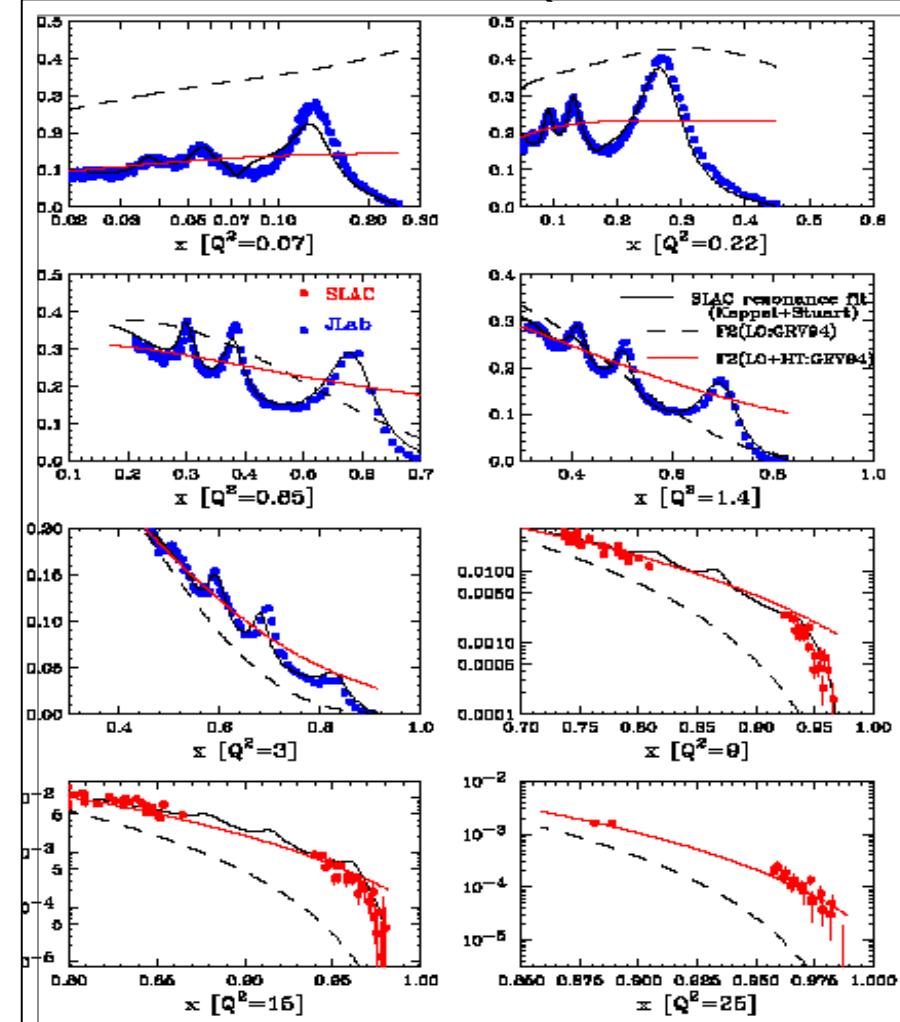
where $x_w = x(Q^2 + 0.624)/(Q^2 + 1.735x)$.

Dashed: GRV94

Red: Bodek-Yang

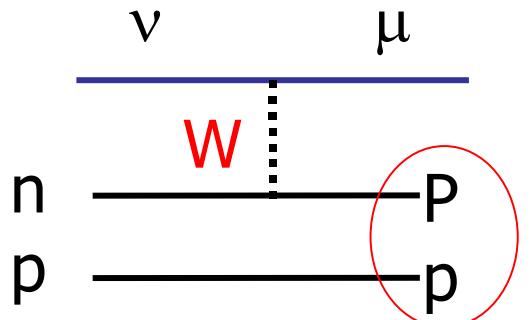
This correction is significant at low Q² region.

SLAC/Jlab resonance data (not used in the fit)

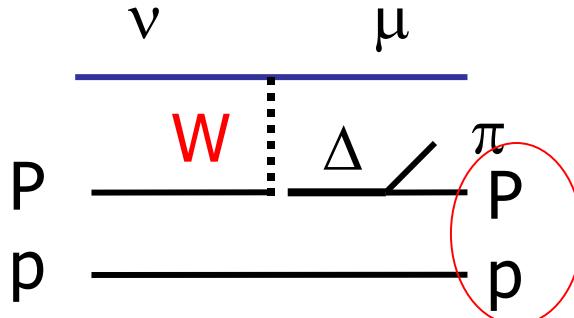


Pauli Exclusion Effect

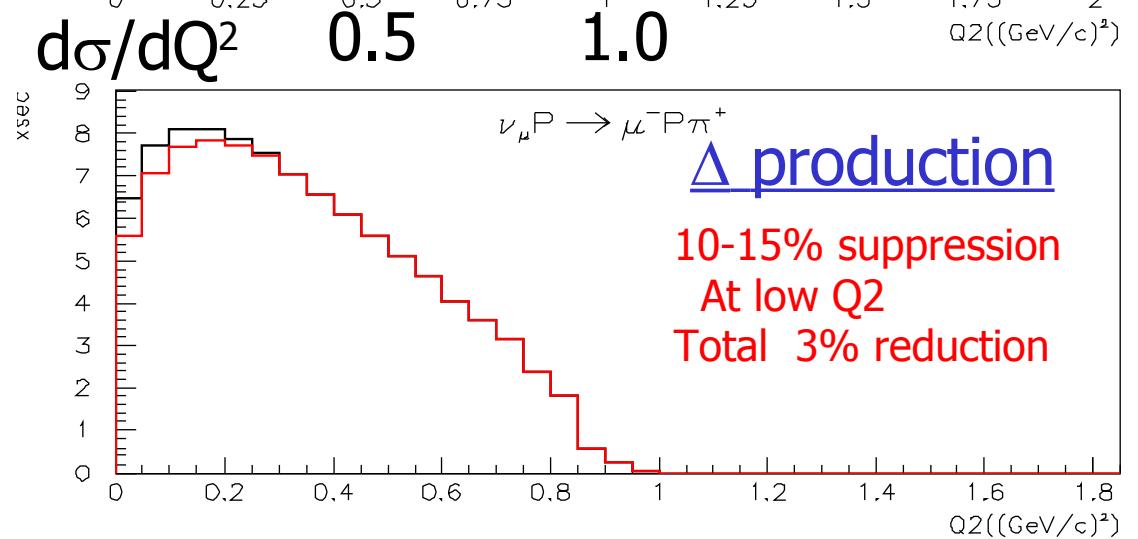
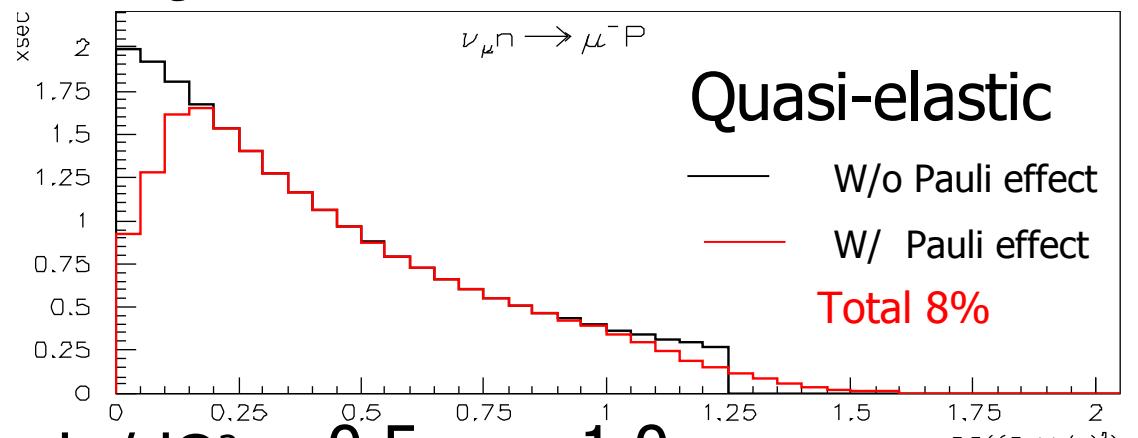
Nuclear effects are large in the low Q^2 region, where the cross section is large.



If $P < k_F$, suppressed.



$$d\sigma/dQ^2 \quad E_\nu = 1.3 \text{ GeV}, \quad k_F = 220 \text{ MeV}/c$$

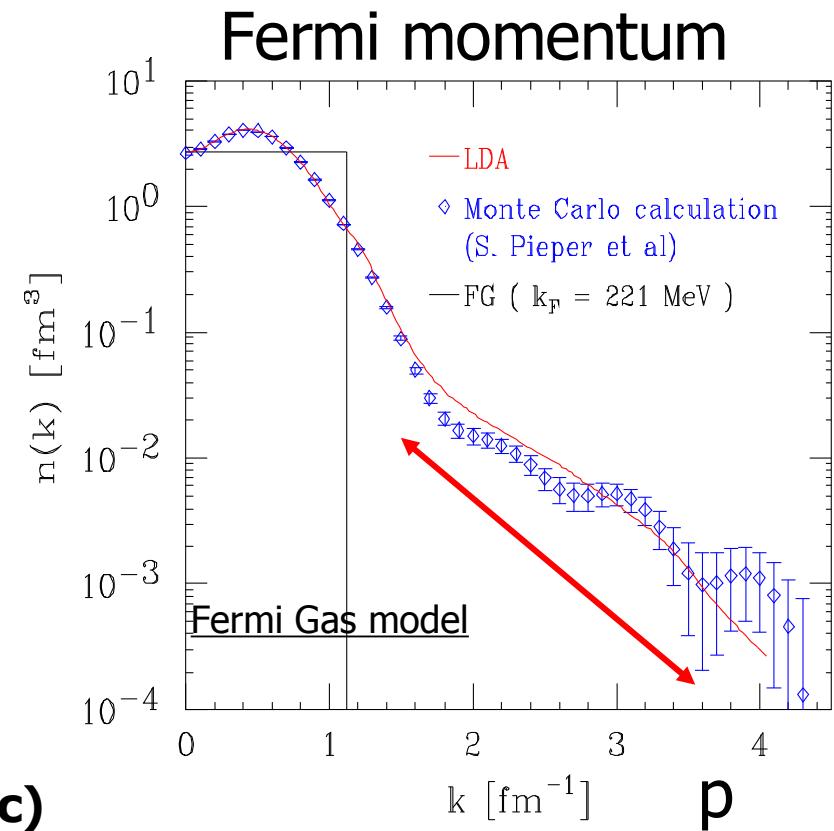
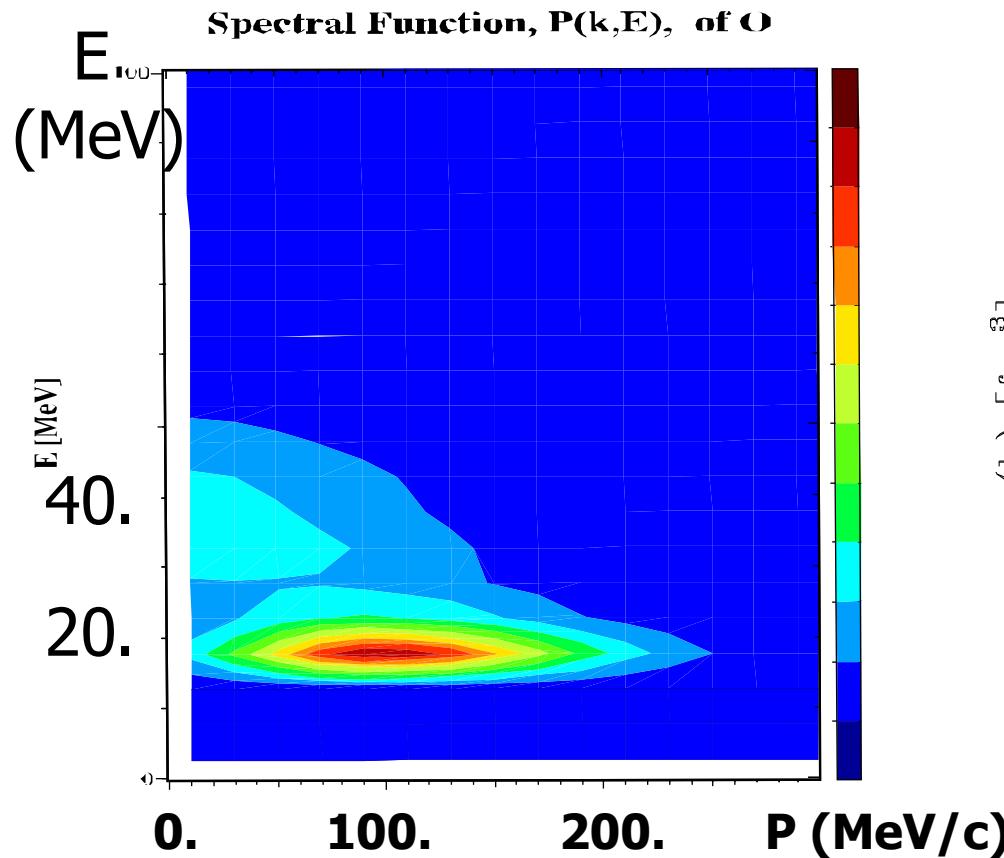


Models beyond the Fermi-gas model

Spectral Function Calculation or Local Density Approximation
(Pandharipande@nuint01, Benhar, Nakamura, Gallagher@nuint02)

Spectral Functions $P(p, E)$ for various nuclei, e.g. ^{16}O , are estimated by Benhar et al. using e-N data.

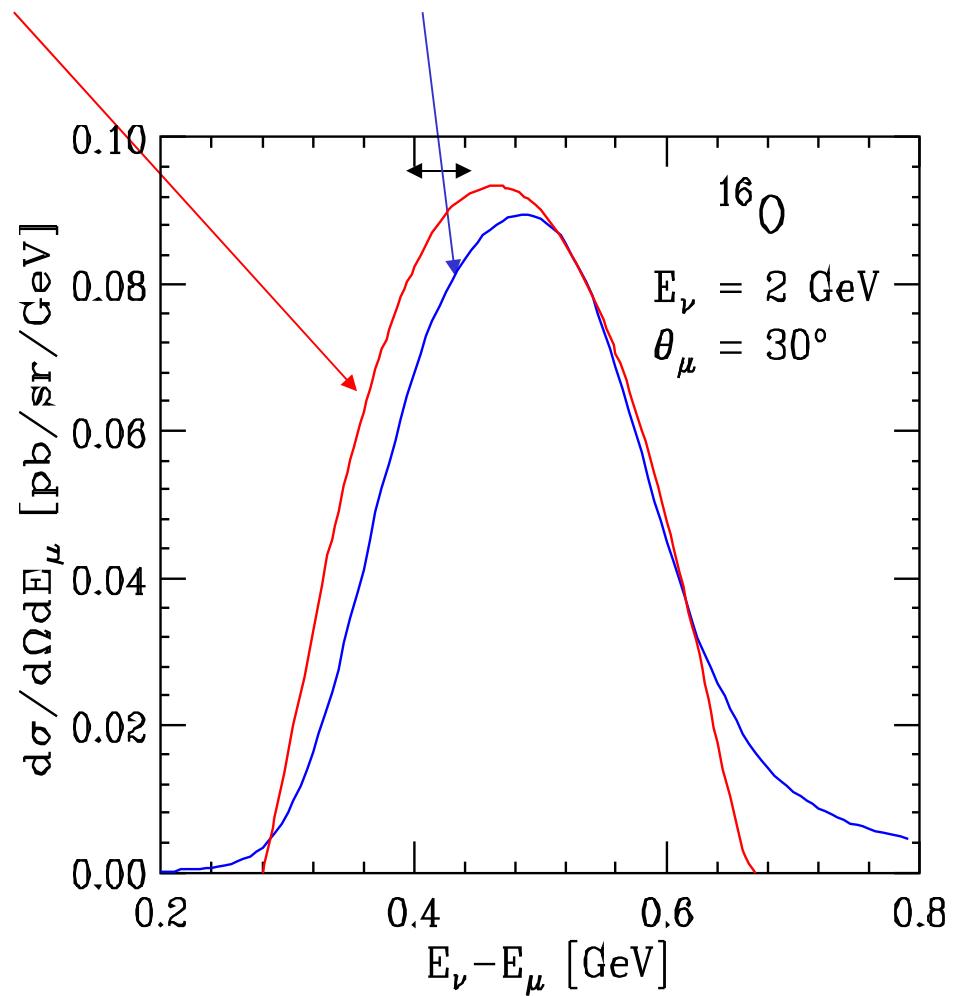
$P(p, E)$: Probability that the target nucleon has momentum p and binding energy E .



Lepton energy in quasi-elastic ν -N interaction

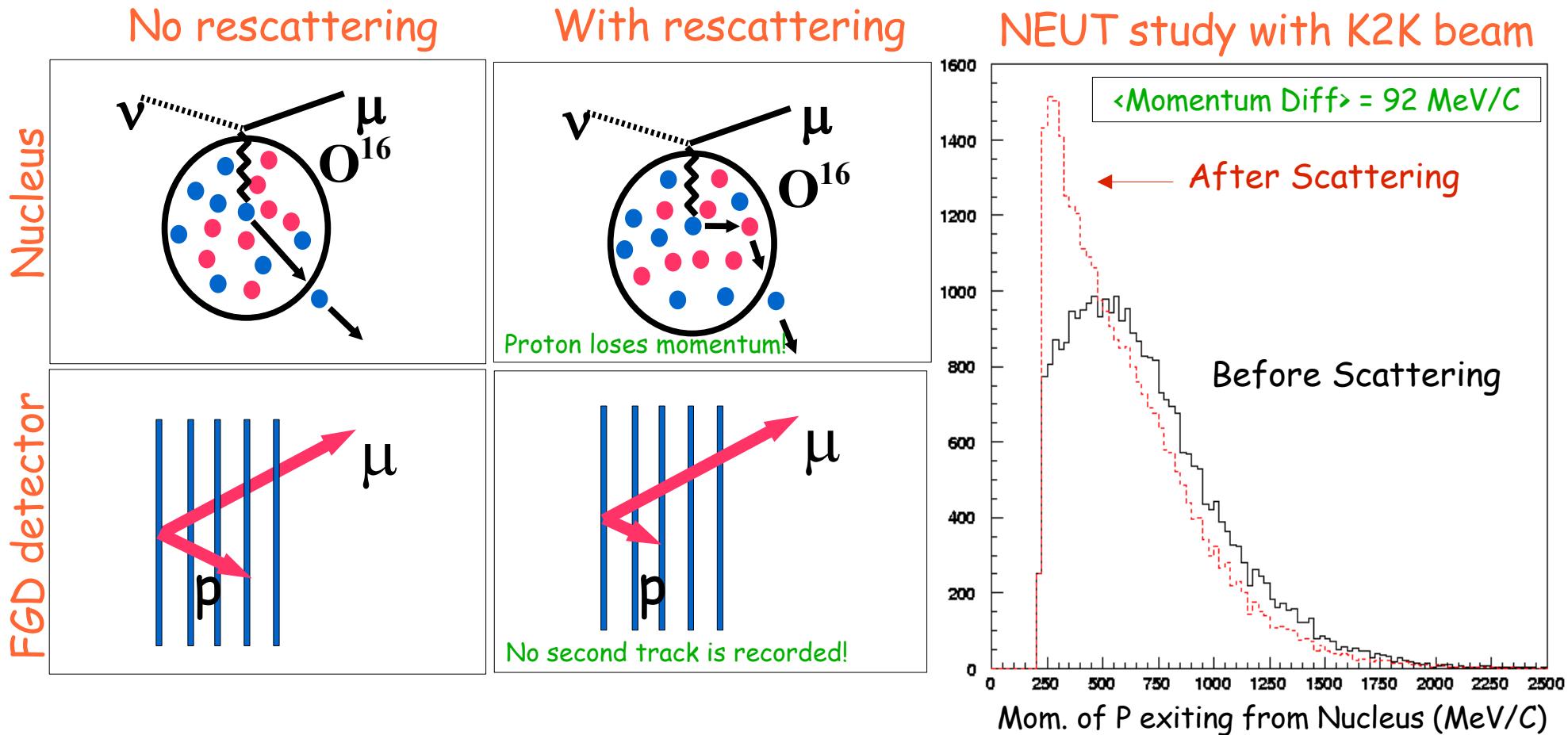
Comparison of **Fermi Gas model** and **Spectral Function Calculation**

- Spectral function gives high energy tail.
- Shift at a level of 10 MeV may exist.
- We can test this using electron scattering data.
- This shift effects the energy of the outgoing lepton and can effect the calculated Δm^2 .



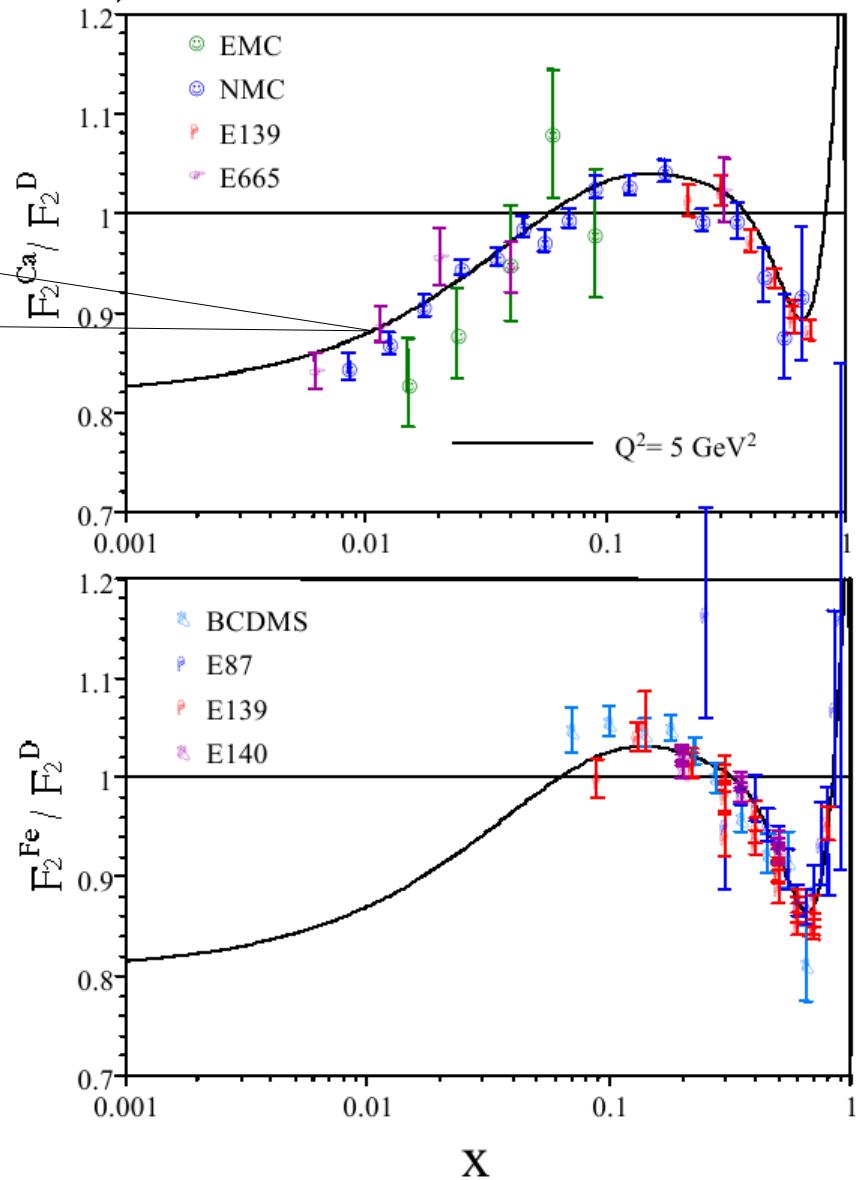
Benhar, Gallagher, Nakamura@nuint02

The effect of proton-rescattering



Nuclear PDFs and the effect on the neutrino xsec

Shadowing
caused by other
nucleons



It seems that the presence
of other nucleons in heavy
nuclei can effect the DIS
cross-section

Kumano @ NuInt02

Use in Experiments:

Need to treat on a equal footing with detector related errors

Example: systematic errors in SK atmospheric analysis

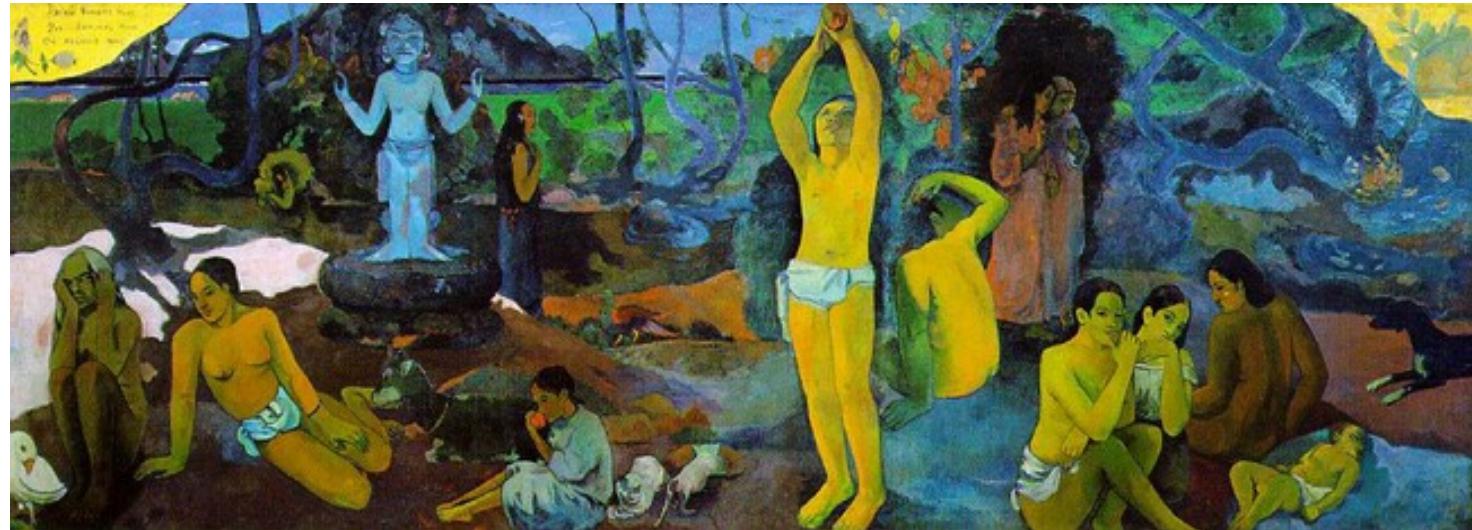
- M_A value in quasi-elastic and single pion
- Quasi-elastic scattering (Difference between two models)
- Quasi-elastic scattering (cross section normalization)
- Single pion production (cross section normalization)
- Multi pion production (With and without B-Y correction)
- Multi pion production (cross section normalization)
- Coherent pion production (with and without coherent CC suppr.)
- NC/CC ratio (Vary ratio of x-secs)
- Nuclear effect in ^{16}O (Change nuclear mean/free path)
- Pion Energy Spectrum (Difference between NEUT and NUANCE)
- CC Tau Production (cross section normalization)

$$\chi^2 = \sum_{n=1}^{370} \left[2 \left\{ N_{exp}^n \left(1 + \sum_{i=1}^{45} f_i^n \cdot \epsilon_i \right) - N_{obs}^n \right\} + 2N_{obs}^n \ln \left(\frac{N_{obs}^n}{N_{exp}^n \left(1 + \sum_{i=1}^{45} f_i^n \cdot \epsilon_i \right)} \right) \right] + \sum_{i=1}^{43} \left(\frac{\epsilon_i}{\sigma_i} \right)^2$$

(11 of about 70 systematic errors)

N_{obs}^n	Number of observed events in n -th bin
N_{exp}^n	Number of expected events in n -th bin
ϵ_i	i -th systematic error term
f_i^n	Systematic error coefficient
σ_i	1 sigma value of systematic error

Where Do We Come From? What Are We? Where Are We Going?



Paul Gauguin 1897-98

NuInt05

Miniboone Anti-nu
Scibar @ miniboone
T2K 280M
T2K 2KM WC+LAr
Minerva

NuInt04

T2K Near Detector
Ideas for future LaR
T2K near detectors
Minerva
Finesse

NuInt02

Finesse
NUMI on axis
NUMI off axis
Lar with Acc.

NuInt01

Scibar Proposal
JLAB overview
NUMI scatt. expt
"small ICARUS" det.

I showed this slide at NuInt05 showing the experimental efforts in this area: Since NuInt01 we made a good start at our work. Let's step back here and understand what we have done, and what we still have to do!

Conclusions

- ▶ If you want to understand neutrino oscillations you need to understand what happens when a neutrino interacts inside of a nucleus.
 - ▶ There are important effects both in the nucleus and in the nucleon.
 - ▶ Different sorts of detectors are sensitive to different neutrino interaction effects.
- ▶ We are now entering the phase where the errors introduced by these effects on measured neutrino oscillation parameters will be of the same size as the statistical errors of experiments.